

## WAFER CELL FOR IMMERSION LITHOGRAPHY

## BACKGROUND OF THE INVENTION

## 1. Field of the Invention

5       The present invention generally relates to lithography for semiconductor fabrication, and in particular, to utilizing a liquid medium through which a semiconductor substrate is illuminated during optical lithography. More particularly, the present invention relates to an immersion  
10 lithography method and apparatus that employs a contained wafer immersion cell to increase the numerical aperture while minimizing sources of photolithographic light obstruction.

## 15 2. Background Information:

Lithography, in the context of building integrated circuits (ICs) such as microprocessors and memory chips, is a highly specialized printing process used to put detailed patterns onto silicon wafers. An image containing the  
20 desired pattern is projected onto the wafer through a mask defining the pattern. Prior to light projection through the mask, the wafer is coated with a thin layer of photosensitive etch resistant material called "photoresist" or "resist". For a positive acting resist, for example,  
25 the bright parts of the image pattern cause chemical reactions which cause the resist material to become more soluble, and thus dissolve away in a developer liquid, wherein the dark portions of the image remain insoluble. After development, the resist forms a stenciled pattern

across the wafer surface which accurately matches the desired mask pattern. Finally, the pattern is permanently transferred onto the wafer surface in an etching process wherein, for example, a chemical etchant is used to etch  
5 the portions of the wafer surface not protected by resist; or the pattern may be transferred by ion implantation in which the resist pattern prevents ions from reaching portions of the wafer surface.

With the image resolution of lithography as a limiting  
10 factor in the scaling of IC devices, improvements in lithographic components and techniques are critical to the continued development of more advanced and compact ICs. The optical lithography scaling limitation for feature width is expressed by the Rayleigh equation:

$$15 \quad W = \frac{k\lambda}{NA}$$

where  $k$  is the resolution factor,  $\lambda$  is the wavelength of the exposing radiation, and  $NA$  is the numerical aperture.  $NA$  may be determined by the acceptance angle of the lens and the index of refraction of the medium  
20 surrounding the lens, as follows:

$$NA = n \sin \alpha$$

where  $n$  is the index of refraction of the medium between the lens and the image plane and  $\alpha$  is the acceptance angle of the lens.

25 Faced with problems and limitations relating to using shorter wavelength light sources, optical lithography developers have increasingly looked for ways of increasing

the NA of lithography systems. Having low radiation absorption characteristics and for ease of implementation, air has traditionally been used as the transmitting medium. However, having an index of refraction  $n=1$ , air as the transmitting medium presents a clear limit to the NA and consequently to the minimum scaling size. Immersion lithography, in which a liquid having a higher index of refraction is used as the medium, is therefore rapidly emerging as an important candidate for upcoming semiconductor lithography applications.

Several immersion lithography techniques are known in the art. One approach, sometimes referred to as the "swimming pool" method, involves wholly or partially submerging the wafer stage, wafer and lens in a pool of immersion fluid, typically water. This technique is referred to as the "bathtub" method when the pool is circulating. Another approach, commonly referred to as the "shower" method, employs nozzles to inject water between the lens and the wafer wherein a suction port for liquid recovery uptakes the injected liquid on the opposite side of the lens after it passes under the lens.

While the foregoing techniques represent progress in the development of this new technology, a number of practical implementation issues remain, including maintaining a pure, non-obstructing transmission medium and compatibility of the tools and wafer with the liquid medium. Purified and degassed water, having a light absorption of 5% at working distances up to 6 mm and an index of refraction  $n = 1.47$ , may be a suitable medium for immersion lithography. However, problems remain relating

to the tendency to form bubbles during the scanning processing. The stage on a lithography exposure tool steps from location to location across a wafer scanning the reticle image for each field. To achieve high throughput, 5 the stage must accelerate rapidly through the immersion fluid, move accurately to the next field location, settle, scan the image and then step to the next location all in a short period of time.

A water medium is susceptible to forming micro bubbles 10 and nano bubbles in the cavitation prone water layer near the moving surfaces, resulting in imaging obstruction and anomalies. Anomalous effects can include absorption, scatter, or an induced birefringent effect with the directional flow of the fluid. Microbubble formation is 15 particularly acute on or adjacent the cavities present in the relatively rough topography at the resist/wafer surface. In addition to problems associated with maintaining purity of the liquid, prior art immersion lithography techniques require substantial redesign of 20 stages for compatibility in a submerged liquid environment requiring significant re-engineering and adding to development costs. Included among the many issues posed by conventional immersion lithography are modifications to lens design and lens casing for compatibility with the 25 resist and immersion liquid, and maintaining immersion liquid properties such as purity, temperature, etc.

From the foregoing, it can be appreciated that a need exists for an improved immersion lithography system and method that substantially increases the NA while minimizing

obstruction and distortion of the scanned image. The present invention addresses such a need.

**SUMMARY OF THE INVENTION**

An apparatus, system and method for use with a photolithographic system are disclosed herein. In accordance with one embodiment, the photolithographic system of the present invention includes a workpiece support member for supporting a semiconductor wafer. A substantially transparent cover member is disposed over said workpiece support member to form a substantially enclosed workpiece cell therebetween. The enclosed workpiece cell is filled with a first immersion fluid having suitable refractive properties. The cover member includes an upper surface contoured to form an open reservoir containing a second immersion fluid in which a final lens element may be immersed during a lithography process.

The foregoing and other objectives, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives, and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein like reference numerals indicate like components, and:

**Figure 1** depicts a cross section of a photolithographic apparatus in accordance with a preferred embodiment of the present invention;

**Figure 2A** illustrates a cross section of a photolithographic system in accordance with a preferred embodiment of the present invention;

**Figure 2B** depicts an alternate view of the photolithographic system shown in **Figure 2A**; and

**Figure 3** is a high-level flow diagram illustrating steps performed during immersion lithography in accordance with a preferred embodiment of the present invention.

**DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT**

The invention will now be described in more detail by way of example with reference to the embodiments shown in the accompanying figures. It should be kept in mind that  
5 the following described embodiments are only presented by way of example and should not be construed as limiting the inventive concept to any particular physical configuration.

Further, if used and unless otherwise stated, the  
10 terms "upper," "lower," "front," "back," "over," "under," and similar such terms are not to be construed as limiting the invention to a particular orientation. Instead, these terms are used only on a relative basis.

15 The present invention is directed toward an improved optical or photolithographic apparatus, system and method in which one or more immersion fluids are utilized to increase the index of refraction and consequently increase the numerical aperture. In one embodiment, the invention  
20 employs a layered liquid immersion technique that enables a semiconductor workpiece to be immersed in the controlled environment of a substantially enclosed cell while a final lens cover element is disposed within a second immersion fluid contained in an open reservoir positioned over the  
25 enclosed cell. As depicted and explained in further detail with reference to the figures, the open reservoir is preferably defined by the upper surface contour of a transparent cell cover that forms the barrier between the enclosed cell and open reservoir. In this manner, the  
30 numerical aperture of a photolithographic light beam passing down from the lens cover, through a first immersion



fluid layer, the cell cover and the second immersion fluid layer, and onto the surface of the semiconductor workpiece is determined by the respective indices of refraction of the fluid and cell cover layers. The divided immersion layering technique of the present invention enables the use of at least two different immersion fluids, one having chemical properties more compatible with the semiconductor workpiece and the other more compatible with the final lens element immersed in the open reservoir. The immersion fluid separation further enables independent monitoring and control of flow, pressure, and temperature of the respective fluid layers.

While the depicted embodiment shows a system that bounds the reservoir by the cell cover, the workpiece and the workpiece support, it should be understood that the present invention applies to other reservoir containment, such as a reservoir bounded by the cell cover and workpiece alone.

With reference now to the figures, wherein like reference numerals refer to like and corresponding parts throughout, and in particular with reference to **Figure 1**, there is depicted a cross section of a photolithographic apparatus **10** in accordance with a preferred embodiment of the present invention. Photolithographic apparatus **10** generally comprises a cell cover member **4** supported by support members **15** and disposed over a workpiece support member **5** to form a substantially enclosed workpiece cell **8** into which a workpiece (not depicted), such as a semiconductor wafer, may be suitably positioned. For a typical lithography exposure process, it may be desirable

to adjust the wafer top surface height as determined by the position of workpiece support member **5** to establish and maintain focus. When used in a photolithographic system for scanning a semiconductor wafer, workpiece support member **5** is preferably a wafer chuck having vacuum ports **7** for securely maintaining a wafer (not depicted) against its upper surface. As explained in further detail below with reference to **Figure 2A**, workpiece cell **8** is designed to contain a suitable immersion fluid such as purified and degassed water which serves as an improved refractive medium compared with gaseous light transmission media such as air, nitrogen, helium, or argon which are used in non-immersion systems.

Photolithographic apparatus **10** further preferably comprises fluid control mechanisms for controlling the condition of a fluid contained within workpiece cell **8**. Specifically, and as shown in **Figure 1**, workpiece support member **5** further includes fluid ingress and egress means in the form of one or more fluid pressurization ports **12** for filling, pressurizing, and circulating the contained fluid during photolithographic scanning.

Given the aim of photolithographic apparatus **10** as providing an optimal transmission medium path for irradiating a workpiece, e.g. a wafer, contained within workpiece cell **8** with a suitable photolithographic light source, cell cover **4** preferably comprises a transparent material selected for low light absorption characteristics. In addition to providing the overhead boundary of workpiece cell **8**, cell cover **4** further includes an upper surface **6** and sidewall members **3** mutually configured to define an

open reservoir volume vertically bounded by the upper edges of sidewall members **3** and disposed in an overlapping manner over workpiece cell **8**. As shown in the depicted embodiment, the open reservoir has a substantially planar bottom surface extending to or slightly beyond the edges of the workpiece cell **8** as defined by support members **15**. The planar bottom surface of the open reservoir is preferably bounded at its peripheral edges by an indented gutter channel **16**. It should be noted that while the depicted embodiment employs an open reservoir implementation, in the alternative, the reservoir supported by cell cover **4** may be enclosed or otherwise covered to prevent contaminants from entering an immersion fluid contained therein.

Referring to **Figure 2A**, there is illustrated a photolithographic system **20** incorporating the constituent components of photolithographic apparatus **10** in accordance with a preferred embodiment of the present invention. As shown in **Figure 2A**, a semiconductor wafer **2** has been positioned at the bottom of workpiece cell **8** such that a fluid layer remains between the upper surface of semiconductor wafer **2** and cell cover **4**. In accordance with standard photolithographic processes, the upper planar surface of wafer **2** is typically covered with a photoresist material (not depicted) that is reactive with the photolithographic light source to define an integrated circuit pattern on the wafer. Vacuum ports **7** are utilized for securely adhering wafer **2** in a specified position on the surface of support member **5**, which may be a wafer chuck in the depicted embodiment. For ease of illustrating the relative disposition of several components of photolithographic system **20**, cell cover **4**, workpiece

support member **5**, and wafer **2** are depicted in cross section.

Photolithographic system **20** further includes a projection assembly **22** that preferably includes devices and components for directing and focusing a light source, such as a deep ultraviolet light beam onto the working surface of wafer **2**. Although not explicitly depicted in **Figure 2A**, such devices and components may include a reticule stage, a shutter stage, multiple lenses and mirrors, and other image projection control equipment familiar to those skilled in the art. While depicted in **Figure 2A** as a discrete entity for ease of illustration, projection assembly **22** may actually comprise several non-mechanically connected and independently movable components and devices.

Among the devices depicted in association with projection assembly **22** are leading and trailing cover normal focus sensors **24** and leading and trailing wafer normal focus sensors **26**. The cover normal sensors **24** provide a real time measurement of the vertical distance from a specified reference point to the cover member surface **6** during a stepping or step-and-scan process. Similarly, wafer normal sensors **26** provide a real time indication of the vertical gap between the projection apparatus **22** and the upper surface of wafer **2** as the lithographic apparatus **10** moves in a planar manner relative to projection apparatus **22** such as during scanning. With the goal of optimizing the lithographic focal point, the feedback from sensors **24** and **26** is used by one or more position control systems associated with either projection assembly **22** or photolithography apparatus **10** to adjust the

relative vertical position of the components of the projection or photolithographic apparatus. It may be necessary to adjust the cover and wafer top surfaces independently. The relative adjustments are preferably  
5 made in accordance with the indices of refraction of the immersion liquids and cell cover.

Most conventional lithographic lenses, such as may be incorporated in a projection apparatus analogous to projection assembly **22**, include a replaceable final lens  
10 element or lens cover. This lens cover element protects the lens from contaminant deposition such as might be present in the air around the lens or might emanate from the resist during exposure in a non-immersion system. In accordance with the preferred embodiment depicted in **Figure**  
15 **2A**, projection assembly **22** includes a final lens element **40** in the form of a lens or lens cover situated in an opposed facing manner with respect to the upper surface **6** of cell cover **4**. Under photolithographic operating conditions, photolithographic apparatus **20** and projection assembly **22**  
20 are mutually positioned in the depicted vertical direction such that the final lens element **40** is at least partially immersed in an immersion fluid **18** contained in the open reservoir formed by the upper surface of cell cover **4**. Serving as the final lens element, the lens or lens cover  
25 **40** preferably comprises a polished, transparent member, and more specifically may comprise synthetic quartz ( $\text{SiO}_2$ ) for 193 nm and longer wavelengths. For 157 nm wavelengths, the synthetic quartz may be modified by removal of  $\text{OH}^-$  and doping with fluorine to improve transmission.

As shown in the depicted embodiment, and with an alternate view depicted in **Figure 2B**, final lens element **40** has dimensions and contouring characteristics for reducing some of the aforementioned problems with conventional immersion techniques relating to minimizing uneven or turbulent fluid flow at the lens cover surface.

Specifically, the side view of projection apparatus shown in **Figure 2A** reveals the elongated dimension and proportion of lens element **40** in parallel with the direction of relative motion between photolithographic apparatus **10** and projection assembly **22**. During a scanning or step-and-scan procedure, photolithographic apparatus **10** moves as a substantially discrete unit relative to projection assembly **22** generally, and final lens element **40** in particular.

The lengthwise dimension of lens element **40** is preferably at least 25 mm in order to minimize the effect of turbulence at the leading and trailing edges (with respect to the indicated direction of travel) of lens element **40** from affecting imaging near the center of the cover.

Furthermore, and as depicted in frontal cross section view (perpendicular to the side view shown in **Figure 2A**) of **Figure 2B**, final lens element **40** further includes lateral runners **44** forming a flow channel **42** beneath the central portion of lens element **40**. The flow channel guides the liquid beneath the lens, resulting in improved and more uniform fluid flow characteristics. The lateral runners **44** protrude downwardly and extend along the outer lengthwise edges of final lens element **40** such that channel **42**, containing immersion fluid **18**, is formed along the bottom lengthwise surface of lens element **40**. In a preferred embodiment, final lens element **40** is disposed with respect

to cell cover **4** such that a fluid filled gap of between 1 to 10 mm remains between the upper surface of cell cover **4** and the bottom planar surface of lens element **40**.

In accordance with the embodiments shown in **Figures 2A** and **2B**, several components of the photolithographic apparatus **10**, including workpiece support member **5** and support members **15** are preferably either a removable or non-removable component of a stage device, such as a servo driven wafer stage, which moves in a planar stepwise manner with respect to the lower exposure surface, including lens element **40**, of projection assembly **22**. With cell cover **4** in the depicted position, the enclosed immersion fluid **19** contained within workpiece cell **8** moves with the unit, thus minimizing fluid flow at the working surface boundary of wafer **2**. In this manner, the present invention substantially eliminates cavitation and other bubble forming stimuli at the wafer surface. The reduction or elimination of microbubbles at the wafer/liquid boundary is particularly important since the effect of obstructing contaminants such as bubbles become more pronounced nearer the target surface.

By layering the fluid boundaries such that the open reservoir is positioned on the lens side of photolithographic system **20**, any bubble or other contaminant formation will have a minimal effect on imaging. This layering method is further enhanced by the intermediate positioning of cell cover **4** that prevents bubbles or other contaminants formed in the open reservoir from reaching the enclosed workpiece cell **8**. In addition, cell cover **4** acts in a manner analogous to a reticule

pellicle in that bubbles or other contaminants contained in the upper immersion fluid reservoir are out of focus and cause less image degradation than would be expected if they were allowed to approach the wafer surface.

5       The substantial fluid isolation of workpiece cell **8** advantageously permits additional fluid control mechanisms to be employed by photolithographic system **20**. Specifically, and as depicted in **Figure 2A**, a fluid pump **23** and associated controller **25** may be used to fill and adjust  
10 the fluid pressure within workpiece cell **8**. In one embodiment, controller **25** receives feedback from cover normal sensors **24** to increase the fluid pressure responsive to cover normal sensors **24** detecting a bow or flex in cell cover **4**. In addition, controller **25** may receive any  
15 combination of pressure, flow, or temperature input signals from one or more sensors (not depicted) that sense the liquid conditions within workpiece cell **8** to maintain an optimum flow, temperature, and/or pressure using fluid control devices such as pump **23** and fluid pressure ports **12**  
20 for maintaining homogeneity of the fluid, particularly of the index of refraction of the fluid, contained within the cell.

A further advantage of the open reservoir as depicted in **Figure 2A** is that it enables photolithographic system **20**  
25 to be utilized in either a "bathtub" or "shower" immersion lithography procedure. To this end, a leading nozzle **32** and trailing nozzle **34** are deployed in the depicted proximity to lens element **40** to discharge and uptake an immersion fluid layer through the channel **42** on the bottom  
30 surface of lens element **40** such as during a scanning or



step-and-scan process in which apparatus **10** moves with respect to projection assembly **22**.

With reference to **Figure 3**, there is depicted a high level flow diagram illustrating steps performed during an immersion lithography process in accordance with a preferred embodiment of the present invention. Following removal of the previous wafer from the object workpiece cell, the process begins as shown at steps **42** and **44** with the lens cover and cell cover inspected and cleaned as necessary for the next scanning iteration. After positioning the wafer on the wafer chuck that has been inspected and dried as necessary (step **46**), the cell cover is closed over the wafer cell and the cell is filled with immersion fluid as depicted at steps **48** and **50**.

Next, as illustrated at step **52**, the cell is positioned under the lens assembly and a scanning procedure is utilized to detect cell cover sag. Responsive to detecting sag in the cell cover, the wafer cell is pressurized as depicted at steps **54** and **56**. The cell is pressurized to compensate and eliminate cell cover sag and the process continues as illustrated at step **58** with a directed flow of the open reservoir fluid via nozzles **32** and **34**. During a stepping or step-and-scan lithography exposure process the lens-to-cell gap and lens-to-wafer focal distance are monitored and adjusted, possibly independently, as necessary (steps **60** and **62**). The process continues until all wafer fields have been covered (step **64**) and the process terminates as shown at step **66**.

It should be understood, however, that the invention is not necessarily limited to the specific process,

arrangement, materials and components shown and described above, but may be susceptible to numerous variations within the scope of the invention.

5           It will be apparent to one skilled in the art that the manner of making and using the claimed invention has been adequately disclosed in the above-written description of the preferred embodiments taken together with the drawings.

10           It will be understood that the above description of the preferred embodiments of the present invention are susceptible to various modifications, changes and adaptations, and the same are intended to be comprehended within the meaning and range of equivalents of the appended  
15 claims.